Efficient Acoustic Uncertainty Estimation for Transmission Loss Calculations

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LONG-TERM GOALS

The overall long-term goal for this project is to enhance the Navy's predictive capabilities in uncertain ocean environments. This project is a collaboration with Dr. Robert Zingarelli at the Naval Research Laboratory - Stennis Space Center (NRL-SSC). At the time of this project's proposal, the long-term goal was the integration of the existing field-shifting algorithm [1,2] with uBand. However, for the uncertain variables of greatest interest to NRL-SSC, alternative reciprocity-based or calculation-statistics-based techniques are likely to provide more accurate results with greater computational efficiently than the field-shifting approach. At present, the long-term goal for this project is to produce techniques and algorithms that improve the performance of uBand for predicting TL uncertainty in underwater environments of interest to the US Navy.

OBJECTIVES

The specific objectives of this project are: *a*) fully explore the applicability and utility of the reciprocity and calculation-statistics approaches for TL uncertainty estimation for uncertain source depth throughout the parameter ranges of interest, *b*) integrate the better of these two techniques into the existing uBand algorithm, *c*) develop other techniques (possibly including FS) for uncertain variables or environments where uBand performs sub-optimally.

APPROACH

The research approach for this project is to hypothesize, develop, and test computationally-efficient techniques for estimating the uncertainty inherent in TL calculations that arises from uncertain sound channel and environmental parameters. Rigorous (but computationally inefficient) direct- or Monte-Carlo simulations are used to develop ground truth for all acoustic uncertainty scenarios and to evaluate the accuracy of various prediction techniques. Simulations in range-dependent environments are performed with the modal-sum propagation model KRAKEN. Simulations in range-dependent

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environments are currently performed using RAMGEO, the computational foundation for the US Navy's Standard Parabolic Equation model (NSPE).

The range-dependent environments of current interest to NRL-SSC are sound channels with simple non-uniform sound speed profiles with upsloping or downsloping bathymetry over ranges of approximately 10 km at frequencies of 100 Hz to 1 kHz. Simulations are conducted in these environments, and the uncertainty predictions of possible uncertainty-prediction techniques are compared to direct simulation or Monte Carlo results.

WORK COMPLETED

Prior research applying the principle of reciprocity was successful for predicting TL uncertainty in range-independent environments, or at a single range of interest in range-dependent environments. Unfortunately, this technique is inefficient for predicting TL uncertainty bounds as a function of range in a range-dependent environment. Thus, for most of FY12, a new approach was pursued based on a combination of the adiabatic approximation, and TL calculations from RAMGEO. This approach had considerable potential due to its basis in acoustic wave-propagation physics, but a workable computational technique for extracting the TL uncertainty that results from source-depth uncertainty has not yet been developed, the primary problem being algebraic inversion of a system of non-linear algebraic equations. Thus, current work is being performed on a third approach based on collecting TL statistics from a single RAMGEO calculation in a range-depth area near the receiver location. This third approach is simpler and should have a clear computational-efficiency advantage over the prior two approaches considered.

RESULTS

The following proportionality is based on the adiabatic approximation to modal-sum propagation in an underwater sound channel. It involves pressure-field-amplitude-squared, since this quantity is directly related to the transmission loss predictions of RAMGEO:

$$\left|p(r,z;z_s)\right|^2 \propto \sum_m \sum_n \Psi_{Sm}(z_s)\Psi_{Sn}(z_s)\Psi_{Rm}(z)\Psi_{Rn}(z)\frac{e^{i\int_0^r k_{rm}(r')dr'}e^{-i\int_0^r k_{rn}^*(r')dr'}}{r\sqrt{k_{rm}(r)k_{rn}(r)}} \tag{1}$$

$$TL = -10\log_{10}\left(\left|p(r,z;z_s)\right|^2 \Big/ \left|p(r=1.0m)\right|^2\right) \tag{2}$$

Here, r is the source-receiver range, z is the receiver depth, z_s is the source depth, Ψ_{Sm} is the m^{th} mode-shape function at the source location, Ψ_{Rm} is the m^{th} mode-shape function at the receiver range, and k_{rm} is the m^{th} horizontal wave number as a function of range. For this TL-uncertainty prediction approach, it was assumed that Ψ_{Sm}, Ψ_{Rm}, and k_{rm} were all known or readily approximated in the environments of interest. Unfortunately, at relevant frequencies and ranges, even small wave number errors lead to unacceptably large errors in the exponential terms in (1). Thus, these factors were treated as unknowns that could be determined near the point of interest by fitting (1) to the RAMGEO calculation. So, to utilize (1) for uncertainty calculations, the following procedure, and many variants of it, were attempted.

(i) Select results for $\left|p(r,z;z_s)\right|^2$ from different range-depth locations from the lone RAMGEO calculation used to predict TL.

(ii) Replace all or part of the exponential factors in (1) with unknowns E_m and E_n.

(iii) Evaluate (1) at the selected locations where RAMGEO results were available to produce a non-linear system of equations for the E_m and E_n.

(iv) Predict TL for different source depths from (1) using the freshly-determined values of E_m and E_n, and the source-depth dependence of the Ψ_{Sm}.

(v) Generate appropriate confidence interval information for TL from the relationship determined in step (iv).

The details are as follows. When $m = n$, the exponential term in (1) has the form

$$e^{-2\int_0^r k_{rmy}(r')dr'} = E_m^2 \tag{3}$$

where k_{rmy} is the imaginary part of the m^{th} horizontal wavenumber. When $m \neq n$, two terms in the doubled-sum of (1) can be combined into one term of the form

$$E_m E_n 2\cos\left(\int_0^r k_{rmx}(r')dr' - \int_0^r k_{rmx}(r')dr'\right) \tag{4}$$

where k_{rmx} is the real part of the m^{th} horizontal wavenumber. By treating either E_m and E_n, or the cosine factor in (4) as unknowns, and matching (1) to the RAMGEO predictions of $\left|p(r,z;z_s)\right|^2$ at multiple receiver depths and ranges, the unknowns can be determined in principle. From such a solution, the sensitivity of TL to source depth changes can be predicted from (1), which in turn readily yield TL uncertainty predictions from source depth uncertainties.

This overall approach yields adequate predictions in cases with extremely low frequencies with few propagating modes, but the presence of many propagating modes presents challenges that have not yet been overcome. Thus, this approach has been currently set aside since it seems likely it will lead to a computationally complicated TL-uncertainty prediction technique that would not be computationally efficient. Future work may revisit this approach, applying further approximations based on range averaging.

The third and current approach is based on computing statistics for $\left|p(r,z;z_s)\right|^2$ directly from the TL predictions provided by the lone RAMGEO calculation. Sample predictions are provided in Figure 1 below for the following conditions. The frequency is 100 Hz. The water-column sound speed is a constant 1500 m/s. The bottom sound speed, density, and absorption are 1700 m/s, 1.5 g/cm^3, and 0.5 dB/λ, respectively. The waveguide depth is 100 m at the source, and it slopes downward to a 200 m depth at a range of 10 km. The source depth is uncertain, with a mean of 40 m and a standard deviation of 1 m. The range-averaged transmission loss is determined from RAMGEO at several receiver depths. Here the range-averaging interval is seven acoustic wavelengths (~100 m for the present case). Statistics are then calculated based on the hypothesis that variations in TL with respect to receiver depth are correlated to variations in TL with respect to uncertain source depth. Figure 1

illustrates the transmission loss uncertainty bound predictions from both this technique (blue) and RAMGEO (red). The prediction using RAMGEO is found by running RAMGEO simulations at multiple source depths, which is computationally inefficient but constitutes ground truth for comparison purposes. The predictions from area statistics utilize just one single RAMGEO calculation. While the curves in Figure 1 are not identical, there is a clear correlation between where the red curves and the blue curves separate, and current work is focused on improving the accuracy of these statistical predictions.

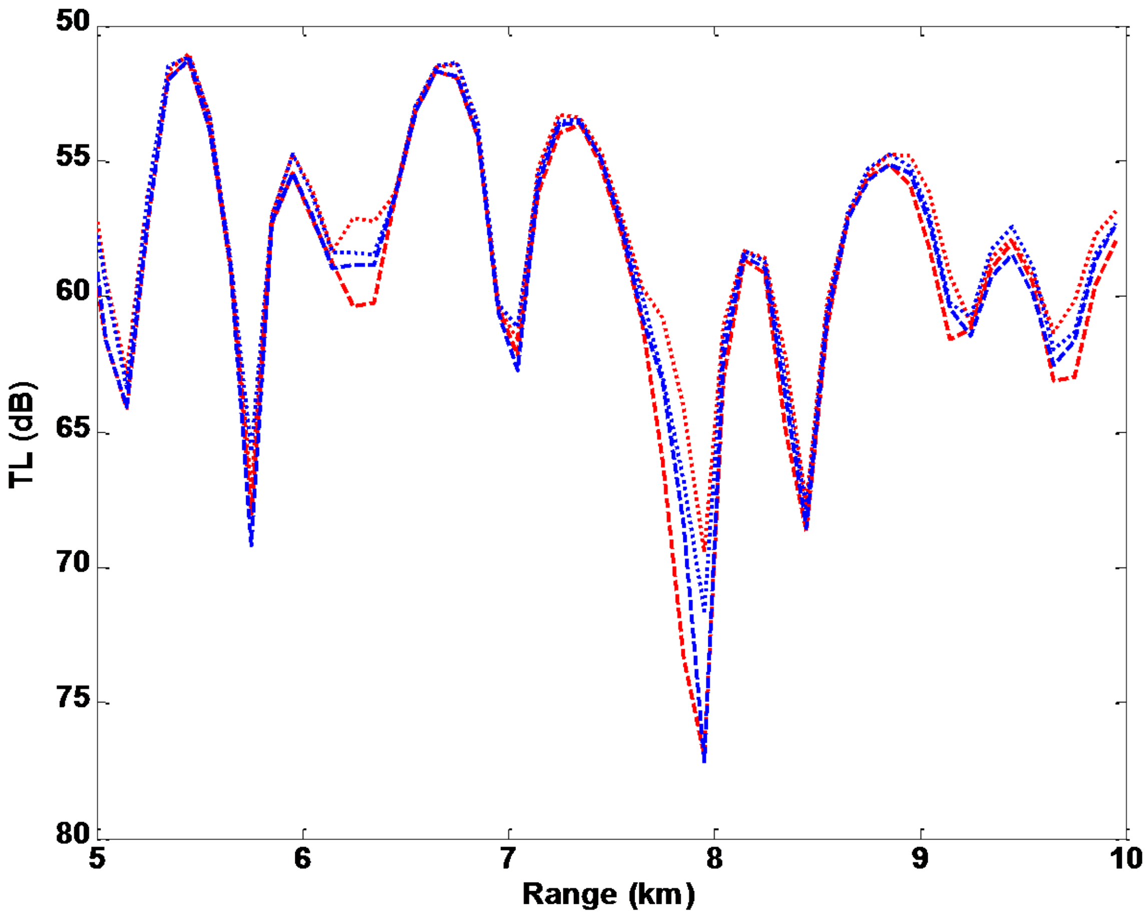

Figure 1. Range-averaged transmission loss uncertainty bounds vs. range. The red lines are generated using many RAMGEO calculations at multiple source depths. The blue lines are generated from a single RAMGEO calculation, and applying the area-statistics technique.

IMPACT/APPLICATION

This project seeks to improve existing Navy TL prediction capabilities by collaborating with researchers at NRL-SSC to optimize acoustic uncertainty prediction algorithms. By addressing many uncertain environmental variables, and working to develop new techniques where current techniques lack accuracy or efficiency, the intended end result should be a robust and efficient computational tool for Navy-relevant transmission loss uncertainty prediction in imperfectly-known ocean environments.

TRANSITIONS

This project has a direct transition path. If successful, this project's results will feed into the uBand algorithm, that is now (or will soon be) a Navy-standard software tool for acoustic uncertainty prediction that is obtainable from the US Navy's Oceanographic and Atmospheric Master Library (OAML) under the Commander, Naval Meteorology and Oceanography Command (CNMOC).

RELATED PROJECTS

This project is a follow-up effort to past ONR-funded work at the University of Michigan on efficient prediction of acoustic uncertainty. In the past decade there has been a significant amount of ONR-funded research on acoustic uncertainty. Foremost among these was the Quantifying, Predicting, and Exploiting (QPE) Uncertainty program lead by Dr. James Lynch that emphasized acoustic experiments. In addition, NRL-DC has a sustained effort in this area focused on polynomial chaos and related techniques under the leadership of Dr. Steven Finette. The project described in this report more closely conforms to Naval applications of acoustic uncertainty prediction than the QPE program and is less computational and mathematical than the NRL-DC effort.

REFERENCES

[1] James, K.R., and Dowling, D.R. (2008) "A method for approximating acoustic-field-amplitude uncertainty caused by environmental uncertainties," *J. Acoust. Soc. Am.* Vol. 124, 1465-1476.

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